Seminar Presentation:

Research on mechanism of HPM dielectric window breakdown and its application

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Content

I Background
II Main research of my dissertation
III Papers and patents
I. Background

Breakdown at vacuum/dielectric interface of HPM window has been a major limitation of power radiation [1]. Methods of improving breakdown threshold become key issues of HPM system [1].

Breakdown is triggered by multipactor and finally realized by plasma avalanche in ambient desorbed or evaporated gas layer above dielectric.

II. Main research of my dissertation

(A) HPM multipactor and breakdown mechanisms

1. Influence of releasing gas on breakdown
2. Space charge field and potential model
3. Model of plasma discharge on a dielectric

(B) Theories and experiments of improving thresholds

4. Periodic retangular surface
5. Periodic triangular surface
6. Resonant magnetic field

(C) Design feed horn and apply periodic surfaces

1. Improved HPM multipactor model

Propose model considering collision and ionization of multipactor electrons with ambient desorption or evaporation gases.
The former models [1,2] assuming vacuum contrast to experiments showing desorption or evaporation gas forming local high p.[3,4]

Tangent and normal velocity:

\[
\begin{align*}
  u_n(t) &= \frac{eE_{\infty}}{mv_n} + \exp(-\nu t) \left( u_0 + \frac{eE_{\infty}}{mv_n} \right) \\
  u_p(t) &= \frac{eE_{\infty} \exp(-\nu t)}{m(\alpha^2 + \nu^2)} \left( a \sin(\phi) + \nu \cos(\phi) \right) - \frac{eE_{\infty}}{m(\alpha^2 + \nu^2)} (a \sin(\alpha \phi) + \nu \cos(\alpha \phi) + \nu^2)
\end{align*}
\]

Collision energy:

\[
\frac{1}{2} \frac{mv^2}{mu^2} = \frac{e^2E^2}{4m(\alpha^2 + \nu^2)} \left( \exp\left(-\nu t\right) + 1 - 2 \cos(\alpha \phi) \exp\left(-\nu t\right) \right)
\]

Transit time: \( (1 - \exp(-\nu t)) \left( u_0 + \frac{eE_{\infty}}{mv_n} \right) \frac{eE_{\infty}}{m} t = 0 \quad \text{Firstly fit } \nu_m \text{ and } \nu_i \)

1. Improved HPM multipactor model

fitting ionization and collision cross-section of N\textsubscript{2} from eV to keV

\[ \sigma_i(\varepsilon) = \frac{4a\varepsilon/\varepsilon_0}{(1+a\varepsilon/\varepsilon_0)} \left[ 1-\exp\left(-\frac{\varepsilon_0-\varepsilon_i}{\varepsilon_0}\right) \right] \]

\[ \sigma_i(\varepsilon) = 1.5*\varepsilon^{1.2}/(1+0.008*\varepsilon^2)^{1.2} +70*\varepsilon/(1+1.05*\varepsilon)^{2.5} \]

Assuming Maxwellian distribution, numerically integrating \( \nu_m \) and \( \nu_i \)

\[ \frac{\nu}{\rho} = \sqrt{\frac{8}{\pi m} \left( \frac{1}{kT} \right)^{1.5}} \int \sigma(\varepsilon) \exp\left(\frac{-\varepsilon}{kT}\right) \varepsilon d\varepsilon \]

---

1. Improved HPM multipactor model

Obtain variation of \( \varepsilon_e \) and saturation boundaries with \( p \). Extend the vacuum solutions\(^{[1]}\) to that under different \( p \).

Calculation: the power deposited by multipactor leads to surface material melting, evaporating, to further improve local pressure

1. HPM experiment research on releasing gas

BWO, 1GW, X-band, 20ns, single and repetitive 50Hz

Distinguished $\Delta P$ for different material

$\Delta P$: PMMA $>$ PE $>$ PTFE $>$ QTZ

$E_B$: PMMA $<$ PE $<$ PTFE $<$ QTZ

Close relation between $E_B$ with $\Delta P$

Deduced $\Delta P \sim 1-10$Torr in 20ns

Guide material selection and conditioning:
Weak SEY, low gas absorption, high melting point; multiple conditioning


2. Space charge field and potential model

Space charge influences multipactor, improves the deposited power. The former model [1, 2] only considered multipactor electrons. Plasma significantly affects field. Propose space charge model of multipactor electrons and plasma

Solving Poisson Equations:

$$\frac{d^2 \psi}{d^2 x} = \frac{n_{el} e^2}{\epsilon_0 T_e} \left( \exp(\psi) + \beta \exp(\alpha \psi) \right) \left( 1 + \beta \right) \left( 1 - \gamma \psi \right)^{\alpha-1}$$

Extend former solution[1] to positive space potential showing $\beta = 1$ curve

Analytical $\phi$ under vacuum:

$$\phi = \frac{2 e}{T_e} \ln \left( \exp \left( \frac{e\phi}{2T_e} \right) + \frac{\alpha e}{v_i} \right)$$

Analytical positive $\phi$ by plasma and multipactor electrons:

$$\Delta \phi = \frac{T_e}{e} \ln \left( \frac{\beta}{\sqrt{\alpha}} \left( 1 + \beta \right) \sqrt{\frac{m_e}{\gamma M}} \right)$$

2. Space charge field and potential model

Plasma leads to further shielding $E_\perp$, improving $P \uparrow$.
Analytical curves agree with PIC simulation [1]
Positive space potential was experimentally found [2]


3. Model of plasma discharge on a dielectric

Strong interaction between HPM dielectric breakdown and plasma discharge in local gas, no corresponding analytical model.

- Density, momentum, energy equation:
  \[
  \frac{dn_t}{dt} = (v_t - (1 - \delta, \delta) v_i) n_t
  \]
  \[
  m \frac{d(n_t u_t)}{dt} = e n_t E - n_t m u_t \cdot \vec{u}_t
  \]
  \[
  \frac{d(3n_T/2)}{dt} = -en_t \cdot \vec{u}_t \cdot \vec{E} - P_{\perp} - P_{\parallel}
  \]
  \[
  P_{\parallel} = n_t v_t e E
  \]
  \[
  P_{\perp} = (e V_{\perp} + T_e) \alpha T_e + 2T_e n_t v_t
  \]
  \[
  \frac{d(T_e)}{dt} = \frac{e^2 V_{\perp}^2}{3 \ln(a^2 + v_i^2)} \left( \frac{2}{3} \delta_e + T_e \right) v_e \cdot \left( \frac{2}{3} \left( e V_{\perp} + 2T_e + T_e \right) - (1 - \delta_e, \delta_e) T_e \right) v_e
  \]
  \[
  \text{Potential drop } V_{\perp} = \frac{T_e}{e} \left( \ln \left( \frac{M}{2 \pi n_t} \right) + \ln (1 - \delta_e, \delta_e) + \frac{1}{2} \ln \left( \frac{\sqrt{\delta_e} + \sqrt{\delta_e}}{\sqrt{\delta_e} + \sqrt{\delta_e}} \right) - \frac{3}{2} \ln \left( \sqrt{\delta_e} + \delta_e, \delta_e \right) \right)
  \]
3. Model of plasma discharge on a dielectric

Considered interaction of plasma and dielectric surface, $\tau$↓

Experiment [2] found, $\tau_{\text{dielec}} < \tau_{\text{space}}$


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(B) Theories and experiments of improving thresholds

4. Periodic retangular surface
5. Periodic triangular surface
6. Resonant magnetic field

(C) Design multi-mode feed horn
4. Multipactor on periodic rectangular surfaces

Periodic dielectric surfaces to alter the trajectories of electrons to decrease $e_e < e_p$ and $\tau << T/2$
Suppress multipactor in developmental stage
Isolate local high pressure and plasma avalanche

$$S_y(T/2) = \sqrt{\pi^2 + 2^2} \frac{eE}{m\omega^2} \sin \left( \frac{\phi - \arctan \left( \frac{2}{\pi} \right)}{\pi} \right)$$

Width $d$ decided by $E_{rf}$, $\omega$, $p$, $E_{dc}$; $d << \lambda$, not to influence HPM transmission

$E_{rf} \uparrow$, $S_y \uparrow$; $E_{dc} \uparrow$, $S_y \downarrow$, $S_x \downarrow$; $p \uparrow$, $S_y \downarrow$, $S_x \downarrow$, $E_{dc}$ and $p$ significant influence

2.86-9.38GHz, $E_{rf}$-30kV/cm
$S_y(T/2)$-0.56-6.1mm

$E_{rf}$
$E_{dc}$
$0.1kV/cm$
$0.5kV/cm$
$1kV/cm$
$1kV/cm, 0.1Torr$
$2kV/cm$
$5kV/cm$
$10kV/cm$
$20kV/cm$
$100kV/cm$
$500kV/cm$
$1000kV/cm$
$2000kV/cm$
$4000kV/cm$
$8000kV/cm$
$12000kV/cm$
$0$ $200$ $400$ $600$ $800$ $1000$ $1200$
$0$ $10$ $20$ $30$ $40$
$10kV/cm$
$E_{dc} = 30kV/cm$
$E_{dc} = 1kV/cm$
$f=2.85GHz$
4. Multipactor 2D-PIC simulation

\[ f = 2.86 \text{GHz} \], \( E_{rf} = 30 \text{kV/cm} \), \( d = 1 \text{mm} \), \( h = 1 \text{mm} \)

\[ \tau_1 < T/2 \), \( F_{ef} \) strong restoring force. SE: \( \tau << T/2, e_e << e_{p1} \), within the duration \( T/2 - \tau_1 \)
4. Proof-of-principle experimental verification

Experiment platform:
Klystron, S-band(2.86GHz), μs width

4. Proof-of-principle experimental verification

<table>
<thead>
<tr>
<th>H/mm</th>
<th>P/mm</th>
<th>Capacity/MW</th>
<th>$E_B$/kV/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>1</td>
<td>&gt;16</td>
<td>&gt;28</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>&gt;16</td>
<td>&gt;28</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>5-6</td>
<td>16</td>
</tr>
<tr>
<td>Flat surface</td>
<td>4</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

When $P_{in}>16$MW, the alumina windows limit power further increasing.

5. Multipactor on periodic triangular surfaces

For rectangular dielectric: multipactor can occur on top and bottom surfaces; sensitive to $p$ and $E_{dc}$.

Analysis of the field convergence and enhancement on periodic triangular surface:

$$\vec{E}_{x} = E_{x} \hat{e}_{x} + E_{y} \hat{e}_{y} = -E_{0} \rho \left( \frac{L}{2} \right)^{-1} \left( \sin(n\theta) \hat{e}_{x} + \cos(n\theta) \hat{e}_{y} \right)$$

Positive effect on multipactor suppression

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5. Multipactor on periodic triangular surfaces

Main courses:

A) flying to-and-from between the slopes and ionizing the ambient gases

B) impacting, multipacting along the slopes until $F_{df}$ reversing
5. Multipactor on periodic triangular surfaces

Multipactor along the slopes:

\[ u(t) = \frac{eE_0(\alpha)\exp(-\nu t)}{m(\omega^2 + \nu^2)} \left( v, \sin \phi - \omega \cos \phi \right) - \frac{eE_0(\alpha)}{m(\omega^2 + \nu^2)} \left( v, \sin(\omega t + \phi) - \omega \cos(\omega t + \phi) \right) \]

\[-\frac{eE_0}{mv} + \exp(-\nu t) \left( u_{in} + \frac{eE_0}{mv} \right) \]

\[ u(t) = \frac{eE_0(\alpha)\exp(-\nu t)}{m(\omega^2 + \nu^2)} \left( v, \sin \phi - \omega \cos \phi \right) - \frac{eE_0(\alpha)}{m(\omega^2 + \nu^2)} \left( v, \sin(\omega t + \phi) - \omega \cos(\omega t + \phi) \right) \]

Transmit time:

\[ \left( \sin \phi - \frac{\omega}{v} \cos \phi + \frac{\nu}{eE_0(\alpha)\nu} \left( u_{in} + \frac{eE_0}{mv} \right) \right) (1 - \exp(-\nu t)) + \sin(\omega t + \phi) \]

\[-\sin \phi - \frac{\nu}{eE_0(\alpha)\nu} (\cos \phi - \cos(\omega t + \phi)) + \frac{eE_0(\alpha)\nu^2}{mv} t = 0 \]

Flying to-and-from between the slopes:

\[ \frac{d(u_i + iu_j)}{dt} + \nu v_i \left( u_i + iu_j \right) + \left( S^* \right)^{\gamma} i eE_0(\alpha) \sin(\omega t + \phi) \frac{m}{m} = 0 \]

5. Multipactor on periodic triangular surfaces

Main factors influencing suppression effect:

Impact energy \( \varepsilon_e \) along slope, Transit time \( \tau \) along slope, Flight time \( \tau_1 \) between slopes

Suppression mechanism: \( e_e < e_0; \ x < T/2 \), small \( \tau \) and \( \tau_1 \), impact number \( \gamma \), decay faster. \( \xi \uparrow, \tau \text{ and } \tau_1 \downarrow \left( E_0 \uparrow, \text{distance} \downarrow \right); A \uparrow, \tau \text{ and } \tau_1 \downarrow \left( E_0 \uparrow, u_y \uparrow \right); \)

Consider \( B \left( E_0 \uparrow \right), \tau \text{ and } \tau_1 \downarrow; \text{f} \uparrow, v(T/2) \text{ and } \tau_1/(T/2) \downarrow; e_0, \tau \text{ and } \tau_1 \text{ decided suppression effect.} \)

Increase \( \xi \), enhance \( E_{rA} \), decrease \( f \), strengthen suppression.
For the same $f=2.86\,\text{GHz}$, $\xi=45^\circ$, $E_{rf}=30\,\text{kV/cm}$

5. Multipactor 2D-PIC simulation

For the same $f$, $\xi$, and $E_{rf}$, larger $P$ with weaker suppression and lower $E_B$

Faster suppression at bottom: $E_{rf}$ convergence, smaller $\tau$; shorter $d$, smaller $\tau_1$;

Weaker suppression upward: $E_{rf}$, $d$, $\tau$, $\tau_1$ ↑

H=1mm, P=2mm

H=3mm, P=6mm

5. Multipactor 2D-PIC simulation

$f=9.4\,\text{GHz}, H=1\,\text{mm}$

For higher $f=9.4\,\text{GHz}$, $\xi=45^\circ$ and $P=2\,\text{mm}$ at $30\,\text{kV/cm}$, no suppression

$\xi=63^\circ$ at $50\,\text{kV/cm}$ effective suppression

Increasing $f$ weakens the suppression effect!
5. Multipactor 2D-PIC simulation

![Graph showing Y vs. X with coordinates and angles]

<table>
<thead>
<tr>
<th>Angle $\xi/^{\circ}$</th>
<th>H/mm</th>
<th>P/mm</th>
<th>Capacity /MW</th>
<th>$E_B/kV/cm$</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1</td>
<td>2</td>
<td>&gt;16</td>
<td>&gt;28</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4</td>
<td>&gt;16</td>
<td>&gt;28</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
<td>11</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>8</td>
<td>6</td>
<td>17</td>
</tr>
<tr>
<td>26.6</td>
<td>1</td>
<td>4</td>
<td>~10</td>
<td>22</td>
</tr>
</tbody>
</table>

Flat surface 4 14

$\xi=45^{\circ}$, P=2mm

By SF$_6$ at 2atm and downstream vacuum, Capacity >36MW and $E_B$ >42kV/cm

$E_B$ dependent on $\xi$ and P consistent with theory, good repeatability

5. Proof-of-principle experimental verification

Experiment platform: Klystron, S-band, $\mu$s width
5. X-band GW HPM experimental verification
BWO, X-band 9.6GHz, 20ns, GW power

For flat, tail erosion, intense reflected peak, pressure rise
For periodic surface, slow erosion

5. X-band GW HPM experimental verification

For flat, $P_{on} \uparrow$, pulse width $\downarrow$, $P_{ref} \uparrow \uparrow$ for $P_{on} > 1$GW, $>10$ times
For periodic, no obvious width $\downarrow$, $P_{ref}$ linearly $\uparrow$, $<<P_{ref}$ of flat

<table>
<thead>
<tr>
<th>$\xi=60^\circ$</th>
<th>H=0.7mm</th>
<th>P=0.8mm</th>
<th>Capacity 1.6GW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat surface</td>
<td></td>
<td></td>
<td>1GW</td>
</tr>
</tbody>
</table>

Physical method of improving $E_{in}$, suitable for different materials
5. Comparison of sawtooth surface on dielectric and metal

Metallic sawtooth surfaces on beam-chamber wall, $E_{rf}$ perpendicular to the slopes, reduce photoelectron emission [1] and SEY [2-3]. Reduction of SEY depends on dimensionless parameter $\xi$ [3], rather than both $\xi$ and $d$, a larger and a smaller grooves, the same restraint.

For dielectric window with parallel $E_{rf}$, restraint depends on both $\xi$ and $d$ related to $f$ and $E_{rf}$.

6. Suppressing multipactor by magnetic field

Mechanism of multipactor suppression:

When $B \perp (E_{rf} \times E_{dc})$ and $\Omega \rightarrow \omega$, resonantly accelerating under $E_{rf} \times B$, impact $e_e > e_p$, $\delta < 1$. More importantly $\tau \sim T$, twice reverses of $E_{rf} \times B$, the same impact and emission phase, SE immediately pull away.

Analytical and simulative agreement of $e_e$
6. Suppressing multipactor by magnetic field

\[ \Omega \sim \omega, \text{ highest resonant } \varepsilon_\omega, \text{ lowest } \delta, \text{ best suppression} \]

\[ \frac{\Omega}{\omega} = 0.7 \]


6. Proof-of-principle experimental verification

Magnet

Klystron system, S-band, 500ns

<table>
<thead>
<tr>
<th>B(T)</th>
<th>Capacity(MW)</th>
<th>( E_0 ) (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.07-0.08</td>
<td>8-9</td>
<td>20-21</td>
</tr>
<tr>
<td>0.09-0.1 (( \Omega \sim \omega ))</td>
<td>&gt;36</td>
<td>&gt;42</td>
</tr>
<tr>
<td>0.12-0.15</td>
<td>17-18</td>
<td>29-30</td>
</tr>
<tr>
<td>Flat surface</td>
<td>4-4.5</td>
<td>14-15</td>
</tr>
</tbody>
</table>

Periodical triangular surface of \( \xi = 45^\circ \) and \( p = 2\text{mm} \) under \( B \sim 0.09-0.11 \), capacity >36MW.
6. Verification the effect for the short pulse

**Research in progress**

- SES device, rectangular waveguide cavity, compress 2μs to 14ns
- Q~8000, Self-breakdown switch, gas of SF₆ and N₂ of 2-4atm, power gain ~ 30-40

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Waveform for dielectric

no B at 52MW, 50kV/cm

Waveform for B~0.07-0.08T at 144MW, 80kV/cm
6. Comparison of mechanism of suppressing multipactor

Alter trajectories, impact energy \( \varepsilon_e \) and transit time \( \tau \) to suppress multipactor

- Periodic rectangular grooved surface
- Periodic triangular surface
- External \( B \perp (E_{rf} \times E_{dc}) \) with \( \Omega \sim \omega \)

Perpendicularly impact the side wall, \( F_{rf} \) plays restoring force until reversing after \( T/2 \)
Periodic slopes diminish the tangent accelerating force and generate a strong normal restoring force
resonantly accelerate under \( E_{rf} \times B \), \( \tau \sim T \), undergo two reverses of \( E_{rf} \times B \) during flights

\[ \varepsilon_e < \varepsilon_{p1}, \delta < 1, \tau < T/2 \]
\[ \varepsilon_e > \varepsilon_{p2}, \delta < 1, \tau \sim T \]

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4. Periodic rectangular surface
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(C) Design feed horn and apply periodic surfaces
7. Design HPM feed horn, cold test and HPM test

Optimize aperture field and radiation patterns of multi-mode horn by CST software. Achieve uniformed aperture field and equal E/H plane far-field.

Agreement of theoretical and experimental radiation patterns:

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III. Published papers and patents

As 1st author, published 9 SCI papers+2 conference papers
10. C. Chang, et al., to be published in Phys. Plasmas (APS-DPP Invited talk)

As 1st inventor, apply for two Chinese national patents with
No.200910121391.1, No.2010101062929

Invited talk in 52nd APS-DPP Annual Meeting in Chicago in Nov. 8-12 2010

Dr. Chao Chang
Tsinghua University
Department of Engineering Physics
Beijing 100084
People’s Republic of China

June 26, 2010

You are invited to attend the Fifty Second Annual Meeting of the American Physical Society: Division of Plasma Physics (APS-DPP) to be held November 8-12, 2010 in Chicago, Illinois, U.S.A. Your invited talk presentation entitled “Review theories and experiments of improving HIPM window breakdown thresholds” will be placed in a technical session. Please visit the Speaker Ready room prior to your talk.
Many thanks!